Moving-bed biological treatment (MBBT) of municipal wastewater: denitrification

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Abstract Denitrification in a full-scale installation and a pilot plant for moving-bed biological treatment (MBBT) was subject to detailed investigation. Two different types of carriers were used in conventional activated sludge reactors: foam cubes and plastic tubes (Kaldnes®).

Both investigated carriers showed the same behavior with regard to denitrification capacity, temperature dependency and maximum COD and nitrate turnover. In contrast to the plastic tubes (Kaldnes®), the sponge cubes stored remarkable amounts of substrate. The maximum denitrification rate with acetate as a substrate was 420 gNm–3d–1 at 10ºC and 730 gNm–3d–1 at 20ºC. An average denitrification rate of 240 gNm–3d–1 (10ºC) was achieved with wastewater. A maximum of 37% of the COD in the influent was denitrified with a volumetric loading rate in the anoxic zone of 2.2 kgCODm–3d–1.

Keywords Moving-bed biological treatment; MBBT; biofilm; full-scale; carrier; wastewater; Kaldnes; PU foam

Introduction

Moving-bed biological treatment

Moving-bed biological treatment (MBBT) is performed in a biofilm system with relatively large (0.1 to 5 cm) carriers. These are mixed with the wastewater and suspended in the reactor by turbulence. The system is located somewhere between an activated sludge and a fixed-bed biofilm system. It does not have to rely on a sludge recycle, as slow-growing microorganisms can be maintained independently of the overall solid-retention time and the danger of clogging is relatively small thanks to the turbulent mixing. By selecting appropriate carriers, conventional reactors for activated-sludge systems could be converted to biofilm systems. This makes the MBBT attractive for introducing nitrification and denitrification to plants with relatively high volumetric loads and low solid retention times (SRT). However, a straightforward implementation of this technique for municipal wastewater treatment is held back by a lack of independent scientific investigations of its performance.

Objective of this paper

This paper reports on the results obtained for the denitrification of low-strength municipal wastewater. Comprehensive investigations were carried out with two different types of carrier in a full-scale installation and a pilot plant. In addition, a brief review is given of the literature relating to the history of wastewater treatment based on suspended carriers.

Overview of literature

The Captor® system (Simon-Hartley) was developed for wastewater treatment based on fermenter investigations (Atkinson et al., 1979–1981). The carriers used were sponge cubes (2.5 × 2.5 × 1.25 cm) made from PU foam. They were suspended in conventional reactors without activated sludge. The advantages claimed were the removal of excess sludge by squeezing the...
carriers off-line (no need for clarifiers), higher volumetric COD turnover and increased oxygen transfer of the aerators (Golla et al., 1994; Reddy et al., 1994). However, independent investigations in England and the USA (Heidmann et al., 1988) were unable to confirm these results.

A similar system was developed in parallel with Captor in Germany, namely the Linpor® system (Linde). It uses smaller sponge cubes (1 × 1 × 1 cm) which are added to a conventional activated sludge system in normal operation. This should increase the amount of biomass so that a higher volumetric COD turnover can be achieved. This direct effect is not apparent from the cases described in the literature, but a decrease of the sludge volume index (SVI) was noticeable after addition of the carriers. This made it possible to increase the suspended sludge concentration (due to the better performance of the clarifier), which does in fact lead to an increase of volumetric turnover (Morper and Wildmoser, 1990).

The literature shows that many other carriers are used for water treatment. Except for the airlift system (vanBenthum et al., 1997), most of these are laboratory investigations and have not yet found their way into practical applications.

One of the latest full-scale developments in this sector comes from Norway: its two variants are called Kaldnes® and Natrix® (both from Kaldnes-Miljøtechnologie). The carriers are small plastic tubes (1 to 5 cm diameter or length) made from polyethylene. The inner part of the tubes is divided into several sectors to increase the total biofilm surface. This system is successfully used for treating high-strength industrial wastewater (Rusten et al., 1993–1996; Pastorelli et al., 1997a/b; Æsøy et al., 1998). Only limited results have been reported for municipal treatment, principally for denitrification but also for nitrification.

Denitrification

The denitrification capacity of a wastewater treatment plant (WWTP) depends mainly on the amount of biodegradable substrate present. This originates either directly from the influent or is produced internally in the reactor by the hydrolytic breakdown of long-chain molecules (generally called hydrolysis). Because of the small amount of readily biodegradable substrate in the influent (low-strength municipal wastewater), hydrolysis is important for the denitrification capacity. A good knowledge of the hydrolysis rates is therefore essential for designing anoxic reactors capable of achieving the desired nitrogen elimination rates.

Definitions

In the following, the difference between the total nitrogen in the influent and the total nitrogen in the effluent of the last reactor (including the suspended biomass) is called the total denitrification, whereas the total nitrogen in the influent minus the soluble nitrogen in the effluent is defined as the total nitrogen elimination.

The filling ratio of the carriers in the reactors is defined as the volume occupied by the carriers in a randomly filled reactor relative to the total volume. All rates are given per reactor volume with a filling ratio of 60% (a typical value for operating an MBBT plant); a linear relationship is assumed between the total biofilm surface and the determined filling ratio. This uncommon but useful unit was chosen because the determination of the active biofilm surface is very inaccurate or even impossible in the case of foam cubes.

All rates are usually given for 10°C. The temperature correction is made on the basis of the following exponential relation: \( r(T_1) = r(T_2) \cdot e^{\theta(T_1-T_2)} \); with \( r(T_1) \) and \( r(T_2) \) = rate at temperatures \( T_1 \) and \( T_2 \), respectively; \( \theta \) = temperature coefficient [ºC⁻¹].

Materials and method

Carriers

The plastic tubes (about 10 mm in diameter and 8 mm long) were acquired from Kaldnes-Miljøtechnologie (KMT). A detailed description of these carriers is given in Rusten et al.
A randomly filled reactor (1 m$^3$) consists of about 1,020,000 carriers and has a volumetric surface of 630 m$^2$ m$^{-3}$ with and 460 m$^2$ m$^{-3}$ without the outer (exposed) surface.

The second type of carriers for the experiments were cubes with an edge length of 10.5 mm. They are cut from commercial polyurethane foam (ironing-board cover material), have a density of 60 kg m$^{-3}$ and contain about 20 pores per centimetre. A randomly filled reactor consists of about 570,000 cubes per m$^3$.

**Pilot plants and wastewater**

Two plants were operated: a pilot plant and a full-scale system. Both plants were continuously supplied with settled wastewater with a total COD of 246 g$_{\text{COD}}$ m$^{-3}$ ($\text{BOD}_5 = 113$ g$_{\text{O}_2}$ m$^{-3}$) and a total nitrogen concentration of 28 gN m$^{-3}$ (ammonia: 19 gNm$^{-3}$). The wastewater contains relatively small amounts of readily biodegradable substrate (less than 10% of the total COD) and has a temperature range of 11 to 20.5°C (5 and 95 percentiles). No chemical precipitants were added and no return sludge was recycled. Internal recycling (including suspended solids) from the last aerated reactor to the first non-aerated one supplied nitrate for the denitrification. The full-scale system was filled with the plastic tube carriers whereas both types of carrier were tested in the pilot plant.

The full-scale system consists of a single lane of a seven-lane wastewater treatment plant (ARA Laufläcker, Turgi, Switzerland), with a total volume of 860 m$^3$, divided into seven compartments (see Figure 1) with brick walls and screens. The average inflow was 3,800 m$^3$d$^{-1}$, proportional to the total inlet of the wastewater treatment plant. The internal recycle from the last to the first reactor had a constant flow rate of 6,080 m$^3$d$^{-1}$. The non-aerated parts were equipped with stirrers, while coarse-bubble aeration in reactors 3, 4A and 4B ensured adequate motion and oxygen supply. Compartments 5 and 6 were provided with fine-bubble aerators. All screens were equipped with additional aerators to disperse heaped carriers in front of the screens with the aid of an air curtain.

The pilot plant consists of five equal reactors with a total volume of 1.6 m$^3$, an average inflow of 6.1 m$^3$d$^{-1}$, and an internal recycle of 7.3 m$^3$d$^{-1}$. As in the full-scale plant, the first two compartments were kept anoxic, whereas the other three were aerated by coarse-bubble aeration. The pilot plant received exactly the same wastewater as the full-scale system.

**Sampling and measurements**

The 24-h composite samples of the influent and effluent (before the secondary clarifier) were collected with a sampler proportionally to the influent flow of the plant. The concentration of ammonia and nitrate in the effluent were monitored on-line and regularly controlled with the 24-h composite and grab samples.
Batch experiments
Some of the batch experiments were performed in the pilot plant by switching off the flow. Good mixing of the 0.3 m³ reactor was achieved with a stirrer (energy input about 100 W). Two lab-scale batch systems were used depending on the type of carrier. The foam cubes were filled directly into a closed 9-l reactor. The temperature in the reactor was held constant and a stirrer prevented carrier sedimentation. A nitrogen atmosphere was maintained to minimize the oxygen input. The Kaldnes® carriers were filled into a 10-l tube of 100 mm diameter. Water is pumped from a second 10-l container through the fixed bed and back to the first container. The residence time of the water in the column was kept shorter than one minute in order to maintain a completely mixed system.

Analytical procedures
Ammonia (colorimetric method), nitrate (reduction on activated cadmium to nitrite) and nitrite (formation of azo-color with sulphanilamide and N-(naphthyl)-ethylenediamine) were measured with a flow injection analyzer (ASIA, ISMATEC AG, CH-Glattbrugg). The measurements were repeated until the resulting signal was within a 2% (relative) error. The COD was determined with a HACH COD kit. For the determination of the total nitrogen, the samples were chemically digested in a 5% (w/w) solution of potassium peroxy-disulphate and 0.7% (w/w) solution of sodium hydroxide at 121°C. After the neutralization, the nitrate concentration was determined.

All chemicals used were of analytical grade and were ordered from FLUKA or MERCK (Switzerland).

Experimental and results
Batch experiments
Batch experiments were performed to determine the temperature dependency and the maximum denitrification rate. Basically, two kinds of experiment were performed for both carrier materials: (i) experiments with acetate added as a readily biodegradable substrate and (ii) experiments without the addition of a carbon source. To avoid limiting the transport of the electron acceptors, nitrate was added in excess to all experiments (> 30 gN m⁻³). The carriers were usually taken from the first anoxic compartment and mixed with water from the effluent of the treatment plant. Figure 2 shows the results of the various experiments.

![Figure 2](https://iwaponline.com/wst/article-pdf/43/11/337/428957/337.pdf)

Figure 2  Volumetric denitrification rates (referred to a filling ratio of 60%). The results for the foam cubes are on the left and those for the plastic tubes on the right. The two graphs on the top are without the addition of an external carbon source, the two graphs on the bottom are with acetate as a readily biodegradable substrate.
i. Experiments with acetate: The experiments with acetate were very similar for both carriers. At 10°C and a filling ratio of 60%, volumetric denitrification rates of 420 g N m\(^{-3}\) d\(^{-1}\) were determined for the foam cubes (Figure 2, bottom left) and 441 g N m\(^{-3}\) d\(^{-1}\) for the plastic tubes (Figure 2, bottom right) with an exponential temperature dependency of 0.055 °C\(^{-1}\) and 0.060 °C\(^{-1}\) respectively.

ii. Experiments without adding carbon: The behavior of the two carriers without an external carbon source differs remarkably. Whereas the foam cubes showed a relatively high denitrification rate of 194 gN m\(^{-3}\) d\(^{-1}\), the plastic tubes had a significantly smaller rate of 130 g N m\(^{-3}\) d\(^{-1}\). Detailed investigation of the foam cubes verified that they are capable of storing large amounts of biodegradable substrate within their pore structures (Maurer et al., 1999). The temperature dependency was determined to be 0.069°C\(^{-1}\) for the foam cubes and 0.058°C\(^{-1}\) for the plastic tubes.

Denitrification capacity with wastewater

Experiments: The maximum denitrification capacity with wastewater as a substrate was investigated for both carriers by adding nitrate in excess to the influent of the pilot plant. After three weeks of continuous adding, the flux of nitrogen and COD was determined in the influent of the first reactor and the effluent of the last one (including suspended solids). The measurements and results are summarized in Figure 3.

COD removal: The measured COD to denitrified N ratio is 9.1 for the plastic tubes and 9.4 for the foam cubes respectively. Assuming that 1 gram of nitrate (N) is equal to 2.86 grams of oxygen as an electron acceptor, about 30% of the total COD in the influent was denitrified for both carriers (plastic tubes: 155.8 gN d\(^{-1}\) × 2.86 gO\(_2\) g\(^{-1}\) N / 1415 g COD d\(^{-1}\) = 32%; foam cubes: 130.9 × 2.86/1229 = 30%).

To estimate the total oxygen demand (COD removal) in the anoxic compartments, the oxygen input must be taken into account. The oxygen input consists mainly of two parts: (i) oxygen from the internal recycle from the last aerated compartment to the anoxic zone and (ii) the oxygen input over the surface due to mixing. The latter can only be estimated via an oxygen transfer coefficient (K\(_{L,a}\)) of typically 5 d\(^{-1}\), which leads to an oxygen input of about 50 g O\(_2\) m\(^{-3}\) Reactor d\(^{-1}\) (K\(_{L,a}\) · O\(_2\) saturation concentration = 5 d\(^{-1}\) × 10.1 g O\(_2\) m\(^{-3}\)). The oxygen concentration in the last reactor was about 4 g O\(_2\) m\(^{-3}\), which leads to a volumetric oxygen input of 29 g O\(_2\) m\(^{-3}\) Reactor d\(^{-1}\). Altogether, the total oxygen input into the anoxic compartment of the pilot plant can be estimated to be about 80 g O\(_2\) m\(^{-3}\) Reactor d\(^{-1}\).
Considering the turnover of both electron acceptors, the micro-organisms were able to respire about 37% of the total influent COD in the anoxic compartment.

**Denitrification rate:** Without considering any aerobic processes, the measured denitrification rates for both carriers were 210 gN m\(^{-3}\) Reactor d\(^{-1}\) (corrected for 10\(^\circ\)C with the temperature coefficient in Figure 2 and for a filling ratio of 60%). Including the oxygen input, the total amount of electron acceptor turnover rate, expressed as nitrate, is approximately 240 gN m\(^{-3}\) Reactor d\(^{-1}\).

**Utilization of methanol:** To test the ability of the fixed biofilm organisms to utilize methanol for denitrification, methanol was added to the wastewater stream during one day at the end of the experiments with the foam cubes. The denitrification then increased significantly by 14% (from 130.9 to 149 gN d\(^{-1}\)), which indicates that a certain ability to utilize methanol is present in the biofilm without adaptation.

**Operation of the WWTP**

The measured overall N elimination of the full-scale plant was 62% (±2.2% for 94 points and a 95% confidence interval). Some of the nitrogen (32%) is incorporated into excess sludge; the rest is due to denitrification. With an average influent to recycle ratio of 1.6, a maximum denitrification of 35% could be expected from the mass balance. This means that the denitrification achieved is nitrate-limited. Sampling at different times during the whole day did indeed show that the nitrate concentrations in the anoxic reactors were low: on average 1.6 gN m\(^{-3}\) in the first and 0.5 gN m\(^{-3}\) in the second anoxic compartment (±0.3 gN m\(^{-3}\) with 28 points and 95% confidence interval for both reactors).

The total COD was 839 kg COD d\(^{-1}\) in the influent and 486 kg COD d\(^{-1}\) in the effluent, and the total nitrogen load was 94 kgN d\(^{-1}\). The denitrification capacity of 30% of the total influent nitrogen is equal to a respiration of 10% of the total influent COD and 23% of the total oxygen requirement for COD removal. This is far below the maximum denitrification capacity measured in separate batch experiments.

The pilot plant showed the same denitrification behavior for both carrier types. Just like in the full-scale plant, the denitrification was mostly nitrate-limited. In addition, no significant denitrification could be detected in the aerobic zone either for the plastic tubes or the foam cubes.

**Discussion**

**Similar characteristics of both carriers**

Both carrier types, plastic tubes (Kaldnes®, KMT) and foam cubes, show similar behavior with respect to denitrification. This is surprising because the plastic tubes were the result of an optimization between the protection of the biofilm in the tubes and the mass flux through the carriers (Hem, 1991). The foam cubes could be expected to have a significantly lower mass flux and therefore also lower turnover rates. The investigation shows that this is not the case at all. Several reasons contribute to this fact.

- **The mass transfer between bulk and foam cubes is relatively high and no worse than that with the plastic tubes.** The equal denitrification rates of acetate and wastewater as carbon sources are strong indications for this. This hypothesis could be confirmed with tracer experiments (Maurer et al., 1999) in which the mixing of a bromide tracer was not delayed by the presence of carriers.
- **Hydrolysis of particulate COD plays a key role for the denitrification rate and capacity.** The foam cubes are capable of storing relatively large amounts of substrate within the carriers (more details in Maurer et al., 1999). The denitrification rates of these storage
products are very close to those with wastewater under operating conditions, but clearly smaller than with acetate. This strongly indicates that the turnover of nitrate is determined by the rate of hydrolysis. In addition, the fact that the foams are capable of flocculating and storing particulate COD means that the denitrification zone can be smaller than for an activated sludge system.

**Specific micro-organisms**

It is assumed that the fixed biofilm adapts to the permanent anoxic conditions with a specific population of denitrifying micro-organisms. In addition, the biofilm structure also helps to maintain extracellular enzymes in the close environment of the excreting organisms. An indirect indication for this hypothesis is the higher hydrolysis rate in this system compared with activated sludge systems (Maurer et al., 1999). This is also apparent from the relatively high denitrification capacity of the wastewater treatment plant. A further hint is the ability of the system to use methanol under anoxic conditions. This differs clearly from observations in activated sludge systems, where a population of methanol-converting denitrifiers must first be induced before they can contribute significantly to N elimination (Purtschert et al., 1999).

**Consequences for wastewater treatment**

Both carriers guarantee good denitrification performance for low-strength wastewater. Good anoxic removal of COD helps to improve nitrification due to increased alkalinity and reduced oxygen turnover in the aerobic zone. Although both carrier materials showed similar denitrification capacities, their mechanical characteristics are completely different. The foam cubes are destroyed more quickly by abrasion and the nitrogen gas produced is trapped within the polyurethane sponges. Unless the anoxic reactors are covered, this leads to floating of the carriers.

**Conclusions**

- Both investigated carriers showed the same behavior with regard to denitrification capacity and temperature dependency.
- The sponge cubes store significantly more particulate substrate than the plastic tubes (Kaldnes®).
- The denitrification capacity of the carriers is very good even with low-strength wastewater. This makes it possible to flocculate and oxidize a significant amount of COD in the anoxic zone, which has a positive effect on the nitrification. If the amount of recycled nitrate is limited, pre-precipitation in the grit-removal tank offers a possible way of removing phosphate without reducing the denitrification capacity. Simultaneous precipitation is not recommended due to clogging of the carriers.
- There are strong indications that the anoxic biofilm develops a well adapted denitrifying population which differs significantly from its aerobic counterpart or that in activated sludge systems. This hypothesis is also supported by the fact that hydrolysis is much faster compared with activated sludge systems.

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